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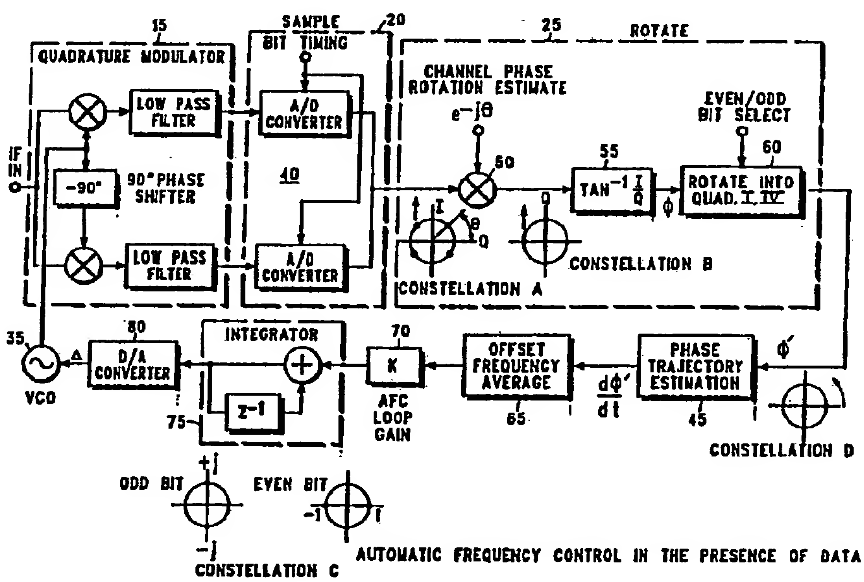

(57) Abstract

There is provided a method of and apparatus for Automatic Frequency Control (AFC) in the presence of data. It comprises removing (25) the effects of data modulated onto the carrier, detecting (30) the frequency difference between the carrier frequency and the phase of the reference oscillator, and adjusting (80) the frequency of the reference oscillator (35) to eliminate the frequency difference (Δ). It is further characterized by digitizing (40) the modulated carrier in quadrature, sampling (20) the modulated carrier in quadrature at a multiple of the modulated bit rate, rotating phases toward arctangent (I/Q) = 0 (25/55/60) to remove the effects of quadrature data (I/Q) modulated onto the carrier, detecting (30) the frequency difference (Δ) between the carrier frequency and the frequency of a Voltage Controlled type of reference oscillator (35) with a phase trajectory estimator (45), and establishing and generating the requisite correction voltage (Δ) for a Voltage Controlled type of reference oscillator (VCO) (35) with the phase trajectory estimator (45).

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AUTOMATIC FREQUENCY CONTROL IN THE PRESENCE OF DATA

THE FIELD OF INVENTION

This invention is concerned with Automatic Frequency Control (AFC). More particularly, this invention is concerned with methods and apparatus for Automatic Frequency Control (AFC) in the presence of data.

BACKGROUND OF THE INVENTION

A persistent challenge arises when attempting to provide Automatic Frequency Control (AFC) in the presence of phase-modulated data. The phase modulation affects the frequency determination required for Automatic Frequency Control (AFC) and unless the effects of the phase-modulation of the data can be removed, AFC in the presence of data will remain a formidable challenge.

This invention then takes as its object to overcome these challenges and to realize certain advantages presented below.

SUMMARY OF THE INVENTION

Thus, there is provided a method of and apparatus for Automatic Frequency Control (AFC) in the presence of data. It comprises removing the effects of data modulated onto the carrier, detecting the frequency difference between the carrier frequency and the frequency of the reference oscillator, and adjusting the frequency of the reference oscillator to eliminate the frequency difference.

It is further characterized by digitizing the modulated carrier in quadrature, sampling the modulated carrier in quadrature at

a multiple of the modulated bit rate, rotating phases toward arctangent (I/Q)=0 to remove the effects of quadrature data (I/Q) modulated onto the carrier, detecting the frequency difference between the carrier frequency and the frequency of a Voltage Controlled type of reference oscillator with a phase trajectory estimator, adjusting the frequency of the reference oscillator by the frequency difference, and establishing and generating the requisite correction voltage for a Voltage Controlled type of reference oscillator (VCO) with the phase trajectory estimator.

DESCRIPTION OF THE DRAWINGS

Additional objects, features, and advantages of the invention will be more clearly understood and the best mode contemplated for practicing it in its preferred embodiment will be appreciated (by way of unrestricted example) from the following detailed description, taken together with the accompanying drawings in which:

The single figure is a functional block diagram of the preferred embodiment and a graphical illustration of its operation.

DETAILED DESCRIPTION

The need for AFC in coherently detecting phase modulated signals arises since even small frequency offsets between the transmitter and the receiver reference frequencies can result in a significant number of detected data errors. To demonstrate this problem, consider the following example. Assume data is sent at a 300 Kb/s data rate using Minimum Shift Keying (MSK) (or a variation of this modulation format, such as Gaussian Minimum Shift Keying, GMSK; Generalized Tamed FM, GTFM; etc.) in a Time Division Multiple Access

system employing time slots of 0.5 msec in duration. Hence a time slot consists of (300 Kb/s) x (0.5 msec) = 150 bits.

Assume further that the phase offset between the transmitter and receiver is adjusted to zero at the start of each received time slot through the use of a synchronization preamble, etc. For noise-free conditions, it can be shown that for an MSK modulation format, bits may be detected without error in the receiver provided that the phase offset between the transmitter and receiver is less than $\pi/2$ radians. As instantaneous frequency is the time derivative of phase, in order for the time slot to be received without error, it is necessary that the phase offset at the end of the slot be less than $\pi/2$ radians, i.e., that the frequency offset between the transmitter and the receiver satisfy

$$f_{offset} \leq \frac{1}{2\pi} \frac{\pi/2}{0.5 \text{ msec}} = 500 \text{ Hz}$$

To accommodate the effects of noise, in practice, it is necessary that the frequency offset be somewhat smaller than this amount, typically 200 Hz.

In a mobile radio operating at 900 MHz, a 200 Hz maximum frequency offset between the transmitter and receiver implies that both the transmitter and receiver must employ oscillators having an overall stability (over time, temperature, etc.) of better than 0.1 parts per million (ppm), a stability requirement currently met only by cesium or rubidium frequency standards and ovenized crystal oscillators. All of these oscillators are too bulky for commercial mobile radio applications. Instead, frequency reference is provided with a smaller oscillator, compromising frequency stability. Methods must be devised for controlling frequency stability in other ways. AFC circuits are one common way.

Conventional AFC circuits, such as described in J.C. Samuels' "Theory of the Band-Centering AFC System", IRE Transactions on Circuit Theory, pp. 324-330, December 1957 (see also the references contained in that paper) are designed to compensate for large frequency offsets between the transmitter and receiver in order to keep the signal within the bandwidth of the receiver's IF filter. This is usually accomplished via a frequency discriminator detector whose output is low-pass filtered to remove any data artifacts from the received signal's mean frequency. Such an approach is useful in achieving frequency offsets of approximately ±1 KHz at center frequency of 900 MHz. It is not an acceptable approach towards achieving a frequency offset of less than 200 Hz unless the transmitted signal bandwidth is less than 200 Hz (e.g., a sinusoid).

The single figure is a functional block diagram of the preferred embodiment and a graphical illustration of its operation. It depicts, coupled in series, QUADRATURE DEMODULATION 15, quadrature (I/Q) sampling (SAMPLE) 20, phase rotation toward a point of coincidence (ROTATE) 25, phase trajectory estimation to detect the frequency difference (DIFF) 30, and a Voltage Controlled Oscillator (VCO) 35.

In operation, GMSK phase-modulated data is quadrature demodulated 15 and digitized, in quadrature, in Analog-to-Digital converters (A/D) 40 as is well understood by those ordinarily skilled in this field. The digitized quadrature information is sampled in quadrature at a multiple of the modulated bit rate (Bit Timing). The I and Q phases are rotated toward a point of coincidence, namely arctangent (I/Q)=0 to remove the effects of quadrature data (I/Q) modulated onto the carrier. Then, the resultant frequency

difference between the carrier phase and the frequency of a Voltage Controlled type of reference oscillator is detected with a phase trajectory estimator 45. Finally, the frequency of the reference oscillator 35 must be adjusted to eliminate the frequency difference by establishing and generating the requisite correction voltage (Δ) for a Voltage Controlled type of reference oscillator (VCO) 35.

The in-phase (I) and quadrature (Q) signals are first rotated 50 by an angle θ to compensate for the phase rotation due to the radio channel between the transmitted carrier and the receiver's reference frequency. The phase of the resulting signal ϕ is then calculated at bit time instants T via the operation arctangent (I/Q) 55. The resulting phases ϕ are subsequently rotated 60 toward a point of coincidence, namely arctangent (I/Q) = 0 to remove the effects of quadrature I-Q data modulated onto the carrier. Then the frequency offset between the received carrier signal and the VCO reference oscillator signal is estimated by means of a linear fit to the phase trajectory estimator 45. The frequency offset estimate is averaged 65 and the average frequency offset is then used to eliminate the frequency offset by establishing and generating the requisite correction voltage Δ for a Voltage Controlled type of reference oscillator (VCO) 35.

Referring to the figure, following demodulation of the intermediate frequency (IF) signal into in-phase (I) and quadrature (Q) signals via a conventional quadrature demodulator 15, the I and Q signals are subsequently converted into digital format signals via two analog-to-digital (A/D) converters 40 operating at a sampling rate equal to a multiple of the data rate (1/T). Noting that an MSK-type signal can also be represented as an Offset-Quadrature Phase Shift Keyed (O-QPSK) signal with a 4-point constellation having

(ideally) points at 0°, 90° 180°, and 270°, the received signal at the output of the A/D converters will, in general, be rotated at an angle θ with respect to the receiver's VCO signal due to the radio frequency channel (Constellation A).

This initial phase offset θ may be estimated via a phase-tracking loop and/or a channel sounding receiver structure.

The initial phase offset θ is compensated for by a complex phase rotation process 50 which multiplies the signal Q + jI by the complex exponential exp $(-j\theta)$, thereby rotating the signal constellation by an angle $-\theta$ and restoring the signal constellation (initially) to the ideal constellation pattern described previously (Constellation B).

The arctangent (I/Q) operation 55 then estimates the angle ϕ at which the received signal is detected. In the absence of a frequency offset and noise, for an MSK signal, the angle ϕ will correspond to one of the four constellation points shown in Constellation B. In general, the phase trajectory ϕ as a function of time is of interest since the time derivative of the phase ϕ <u>in the absence of data modulation</u> is proportional to the frequency offset between the received carrier signal and the VCO signal. In the presence of data modulation, however, the time derivative of ϕ will also be a function of the received data.

To eliminate the effects of the quadrature I-Q data modulated onto the carrier from the offset frequency estimation process, the angle ϕ is rotated 60 into quadrants I and IV as decribed below:

As already noted above, an MSK-type signal can also be described as an O-QPSK signal. This implies that at bit-time spaced intervals, the signal (Constellation B) may be

represented as either a two-bit (biphase) odd-bit constellation with points at $\pm 90^\circ$ or as a two-bit even-bit constellation with points at 0° and 180° (see Constellation C). The two two-bit constellations alternate every bit time. The rules for rotating phases (ϕ) into quadrants I and IV thus become:

EVEN BIT

INITIAL PHASE ϕ	FINAL PHASE ϕ'
$-90^\circ \leq \phi \leq 90^\circ$	$\phi' = \phi$
$-180^\circ < \phi < -90^\circ$	$\phi' = \phi + 180^\circ$
$180^\circ > \phi > 90^\circ$	$\phi' = \phi - 180^\circ$

ODD BIT

$\phi > 0^\circ$	$\phi' = \phi - 90^\circ$
$\phi < 0^\circ$	$\phi' = \phi + 90^\circ$

Note that even though no actual data bit values are determined in this phase rotation process, the effects of data modulated onto the carrier are effectively removed by rotating 60 the phase ϕ in this manner into quadrants I and IV as shown in Constellation D, i.e., all four constellation points of Constellation B have now been mapped into a single point at 0°.

In the absence of frequency offsets and noise, the last statement is true only for pure MSK. For GMSK signals, the mapping $\phi \rightarrow \phi'$ described above will only map the four quadrants into quadrants I and IV due to the data filtering effects present in GMSK signal generation. Nevertheless, this latter phase rotation 60 has effectively removed the effects of quadrature data on the received carrier.

The phase trajectory of the rotated angle ϕ' as a function of time is then used to estimate the actual frequency offset 45. As noted above, the instantaneous frequency is equal to the time derivative of the phase. In the absence of noise, with the effects of data removed from the recovered, phase-rotated phase signal ϕ', the instantaneous frequency is proportional to the frequency offset between the received carrier frequency and the VCO 35. Hence, the phase trajectory estimation block 45 estimates the phase trajectory of ϕ' as a function of time and processes the phase trajectory to estimate the instantaneous frequency.

Three methods may be employed by the phase trajectory estimation block 45 to estimate the frequency offset:

(1.) Take the discrete-time time derivative of ϕ' via the operation

$$\hat{f}_{offset} \approx \frac{\phi'|_{time = t_2} - \phi'|_{time = t_1}}{t_2 - t_1}$$

for every time t_i. The frequency offset $\hat{f}_{offset}$ must be subsequently smoothed to remove any noise artifacts.

(2.) Let $\phi'_i = \max\,[\phi'_1, \phi'_2, \ldots \phi'_n]$ and

$$\phi'_j = \max\,[\phi'_m, \phi'_{m+1}, \ldots \phi'_{m+n+1}]$$

where $\phi_1, \phi_2, \ldots$ are <u>consecutive</u> values of ϕ' at bit time instants and $m >> n$.

Then $\hat{f}_{offset} \approx \dfrac{\phi'_j - \phi'_i}{j - i}$

(3.) Form a least squares linear fit to the ϕ'. The slope of the least squares linear fit is proportional to the instantaneous frequency; i.e. if $\phi'_{-m}, \phi'_{-m+1}, \ldots \phi'_{o}, \phi'_{1}, \phi'_{m}$ are a collection of 2M+1 equally-spaced values of ϕ', then the least-squares linear fit has a slope of

$$\hat{f}_{offset} = \frac{\sum_{n=-m}^{m} n\,\phi'_{n}}{\sum_{n=-m}^{m} n^{2}}$$

Following phase trajectory estimation the output of the phase trajectory estimation block 45 is subsequently filtered (via a first-order IIR filter of the type well-understood by those ordinarily skilled in this field) 65, multiplied by a gain constant K (which also determines the loop dynamics) in multiplier 70, then fed to integrator 75 and converted back into an analog signal via a Digital-to-Analog converter (D/A) 80. The output of the D/A converter 80 provides a correction voltage Δ to the VCO 35 which adjusts the frequency of the VCO 35 to compensate for the offset frequency error.

In summary then, there has been provided a method of and apparatus for Automatic Frequency Control (AFC) in the presence of data. It comprises removing the effects of data modulated onto the carrier, detecting the frequency difference between the carrier frequency and the frequency of the reference oscillator, and adjusting the frequency of the reference oscillator to eliminate the frequency difference.

It has further been characterized by digitizing the modulated carrier in quadrature, sampling the modulated carrier in quadrature at a multiple of the modulated bit rate, rotating phases toward arctangent (I/Q)=0 to remove the effects of quadrature data (I/Q) modulated onto the carrier, detecting the frequency difference between the carrier frequency and the frequency of a Voltage Controlled type of reference oscillator with a phase trajectory estimator, adjusting the frequency of the reference oscillator by the frequency difference, and establishing and
generating the requisite correction voltage for a Voltage Controlled type of reference oscillator (VCO) with the phase trajectory estimator.

While the preferred embodiment of the invention has been described and shown, it will be appreciated by those skilled in the art that other variations and modifications of this invention may be implemented. For example, the phase trajectory estimator may be replaced with either a fixed Wiener filter which estimates the time derivative of the phase ϕ' using a minimum mean square estimate method or with a recursive Kalman filter to estimate the time derivative of ϕ'.

These and all other variations and adaptations are expected to fall within the ambit of the appended claims.

CLAIMS

What we claim and desire to secure by Letters Patents is:

1. A method of Automatic Frequency Control (AFC) in the presence of data characterized by:

removing (25) the effects of data modulated onto the carrier, detecting the frequency difference between the carrier frequency and the frequency of the reference oscillator (35), and adjusting (80) the frequency of the reference oscillator (35) to eliminate the frequency difference (Δ).

2. The method of Claim 1, characterized in that the effects of data modulated onto the carrier are removed by rotating (60) phases toward a point of coincidence (25/55/60).

3. The method of Claim 1, characterized in that the effects of quadrature data (I/Q) modulated onto the carrier are removed by rotating (60) phases toward arctangent (55) (I/Q)=0.

4. The method of Claim 2, characterized in that the time rate of change of the phase rotation is the frequency adjustment required for the reference oscillator (35).

5. The method of Claim 3, characterized in that the difference from zero is determined with a phase trajectory estimator (45).

6. The method of Claim 5, characterized in that the phase trajectory estimator (45) is further employed to establish and generate the requisite correction voltage (Δ) for the reference oscillator (35).

7. The method of any of Claims 2 to 6, characterized in that the phase rotation (25) is preceded by sampling (20) the modulated carrier in quadrature at a multiple of the modulated bit rate.

8. The method of Claim 7, characterized in that sampling (20) is preceded by digitizing (40) the modulated carrier in quadrature.

9. The method of any of Claims 1 to 8, characterized in that the data is GMSK phase-modulated onto the carrier.

10. A method of Automatic Frequency Control (AFC) in the presence of GMSK phase-modulated data characterized by:

digitizing (40) the quadrature-modulated carrier,

sampling (20) the quadrature-modulated carrier at a multiple of the modulated bit rate,

rotating (25) phases toward arctangent (I/Q)=0 point to remove the effects of quadrature data (I/Q) modulated onto the carrier,

detecting (30) the frequency difference between the carrier frequency and the frequency of a Voltage Controlled type of reference oscillator (35) with a phase trajectory estimator (45),

establishing and generating the requisite correction voltage (Δ) for a Voltage Controlled type of reference oscillator (35) with the phase trajectory estimator (45).

11. Apparatus for Automatic Frequency Control (AFC) in the presence of data characterized by, coupled in series:

means (25) for removing the effects of data modulated onto the carrier and

means (45, 80) for detecting the frequency difference (Δ) between the carrier frequency and the phase of the reference oscillator (35) and for adjusting the frequency of the reference oscillator (35) by the frequency difference (Δ).

12. The apparatus of Claim 11, characterized in that the data effects removing means (25) is capable of rotating phases toward a point of coincidence to remove the effects of data modulated onto the carrier, and said detecting and adjusting means (45, 80) is capable of establishing and generating the requisite correction voltage (Δ) for reference oscillator (35).

13. An apparatus for Automatic Frequency Control (AFC) in the presence of GMSK phase-modulated data characterized by, coupled in series:

means (40) digitizing the quadrature-modulated carrier,

means (20) sampling the quadrature-modulated carrier at a multiple of the modulated bit rate,

means (25) for rotating phases toward arctangent (I/Q)=0 to remove the effects of quadrature data (I/Q) modulated onto the carrier and

means (45) for detecting the frequency difference (Δ) between the carrier frequency and the frequency of a Voltage Controlled type of reference oscillator (35), and for establishing and generating the requisite correction voltage (Δ) for a Voltage Controlled type of reference oscillator (35).

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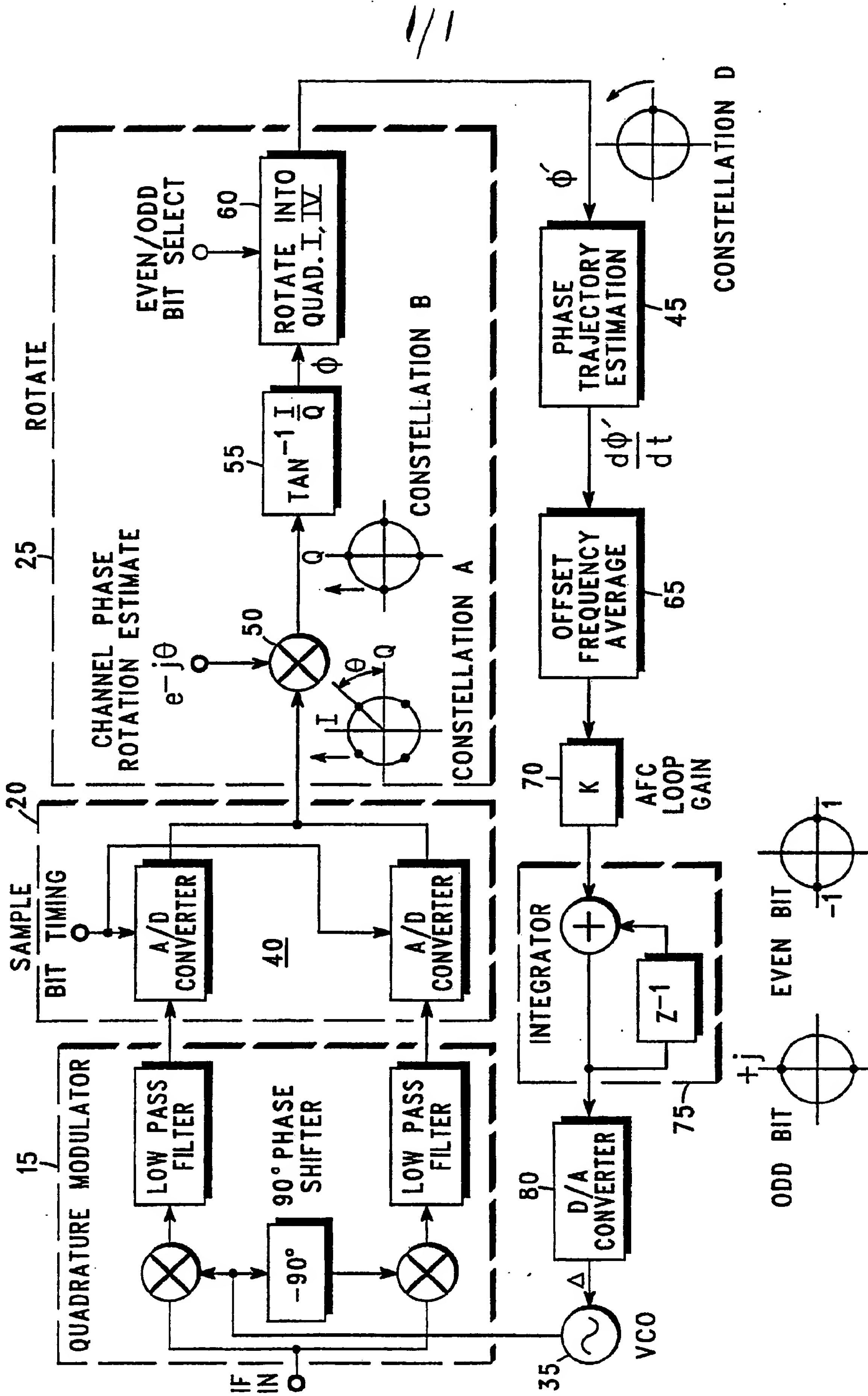

AUTOMATIC FREQUENCY CONTROL IN THE PRESENCE OF DATA

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US89/05780

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC 5 H04L 27/06 //H04L 27/02 // H04L 27/32
USCL 375/97

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
USCL	375/39,77,97 329/122

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
Y	US,A 4,583,048 (Gumacos et al) 15 April 1986 See Columns 7 and 8 and Figure 3	1-4 and 6-13
Y	US,A 4,686,688 (Chung et al) 11 August 1987 See Column 2, lines 60-66	9 and 10
Y	US,A 4,583,236 (Kromer et al) 15 April 1986 See Figure 7	5 and 10
Y	US,A 4,466,108 (Rhodes) 14 August 1984 see figure 1.	1-13

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
21 Janaury 1990	21 FEB 1990
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